Discovery Potential of *R*-hadrons with the ATLAS Detector at the LHC

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Abstract. *R*-hadrons are predicted in a range of supersymmetric scenarios including split-supersymmetry and gauge-mediated supersymmetry breaking. In this paper, the discovery potential of the ATLAS experiment for gluino and stop-based *R*-hadrons is outlined. A range of final state observables such as high transverse momentum muon-like objects and information on ionization energy loss is used. It is shown that ATLAS would be able to discover such particles at comparatively modest amounts of luminosity ($1\mathrm{fb}^{-1}$) for masses up to 1 TeV.

Keywords: high-energy elementary particle interactions, sparticle production, long-lived, massive
PACS: 14.80.Ly,12.60.Jv,13.85.Fb

ATL-PHYS-PROC-2009-086
08 September 2009

INTRODUCTION

The presence (or absence) of massive exotic stable hadrons will be an important observable in the search for and quantification of any new physics processes seen at the LHC. Stable exotic coloured particles are predicted in a range of SUSY scenarios (see, for example, Ref. [1]). Such particles could be copiously produced at the LHC and sensitivity to particle masses substantially beyond those excluded by earlier collider searches ($\lesssim$200 GeV [1]) could be achieved at ATLAS even with rather modest amounts of integrated luminosity ($\sim 1\mathrm{fb}^{-1}$) [2]. This paper outlines a strategy for the detection of exotic massive, long-lived hadrons (so-called *R*-hadrons) formed from either stable gluinos or stops ($R_{\tilde{g}}$ and $R_{\tilde{t}}$-hadrons, respectively). The $R_{\tilde{g}}$-hadrons ($R_{\tilde{t}}$-hadrons) are considered in the context of a Split-SUSY (stop NLSP/gravitino LSP) scenario [3]. Although this work is performed in the framework of SUSY, the techniques presented here may be used in generic searches for stable heavy exotic hadrons.

EVENT GENERATION

The leading-order event generator PYTHIA [4] was used to produce samples of pair-produced gluino and stop-antistop events for a range of gluino and stop masses between 300 and 2000 GeV. The number of expected pair-production events for 14 TeV proton-proton collisions with $1\mathrm{fb}^{-1}$ of integrated luminosity is 2.7×10^5 and 7.8×10^3 for 300 GeV gluino pairs and stop pairs, respectively; for a mass of 1000 GeV, it is 138 and 6, respectively. Production mechanisms of stops and gluinos are illustrated in Figure 1, which shows leading-order Feynman diagrams. The cross section depends principally on the mass of the heavy object under study and not other free SUSY parameters.

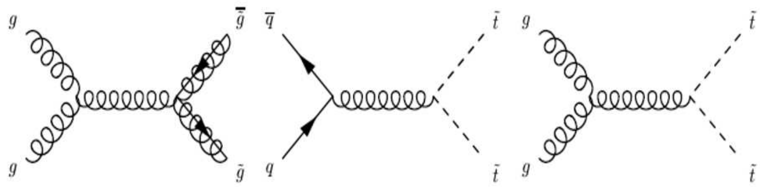

FIGURE 1. Selection of leading-order processes illustrating the production of gluino and stop particles.

To complement the signal samples, various background samples were used, each corresponding to an integrated luminosity of at least ~ 1 fb^{-1}. As the simulated trigger used for this analysis requires a hard muon-like track, only events which could give rise to a high p_T-muon ($p_T > 150$ GeV) were simulated. The following processes were considered : leading-order 2-to-2 QCD processes, which include all quark flavours except top ; backgrounds arising from diboson and single boson production, denoted electroweak ; and a sample of $t\bar{t}$ pair-production events, termed top.

SIMULATION OF *R*-HADRON SCATTERING IN MATTER

A model of *R*-hadron scattering [5] implemented in Geant4 [6] is used in this work. This is an update of earlier work [7] in which the geometric cross-section and phase space arguments are used to predict the different 2-to-2 and 2-to-3 reactions. Other approaches to modelling *R*-hadron scattering have been proposed, based on Regge phenomenology [8]. These yield predictions of energy loss and scattering cross-sections which are qualitatively similar to those given by the model used here [9].

The typical energy loss per interaction is predicted to be low (around several GeV [5]). This implies that the fraction of *R*-hadrons which would be stopped during their traversal of the detector is negligible[1].

Another feature is the possibility of charge and baryon number exchange. Following repeated scattering $R_{\tilde{g}}$-hadrons and $R_{\tilde{t}}$-hadrons not containing an anti-stop should enter the muon system predominantly as baryons. This is due to the occurence of meson-to-baryon conversion processes for which the inverse reaction is suppressed [7]. Anti-baryons would be expected to quickly annihilate in matter and $R_{\tilde{t}}$-hadrons containing anti-stops would thus largely remain as mesons. In the model used here, charged *R*-baryon states are stable and thus are expected to leave tracks in the muon system (although this assumption is now disputed in the case of the $R_{\tilde{g}}$-baryons [9]). Also, a substantial rate of events is expected in which a *R*-hadron appears to possess different values of the electric charge in the inner detector and muon system. While such topologies represent a challenge for track reconstruction software, they also provide observables useful for the discovery and characterisation of *R*-hadrons (see next section).

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[1] Although it does not form a part of this work, the possibility of observing the decay of stopped *R*-hadrons offers a promising and complementary means of searching for *R*-hadrons at the LHC [10, 11].

EVENT SELECTION

The selected level 1 trigger is the *mu*6 trigger [2], which is sensitive to the 'classic' stable massive particle signature of a high transverse momentum muon-like track. Here, we consider events in which a *R*-hadron track in the muon system must be associated with the correct bunch crossing. This leads to a rapid fall in efficiency for $\beta \lesssim 0.6$. After including requirements that the event filter is passed and the muon-like track is well-reconstructed, the overall efficiency is around 15% for $R_{\tilde{g}}$-hadrons and around 25% for $R_{\tilde{t}}$-hadrons, with little mass dependence. Ongoing work involve the development of triggers which do not rely on linked inner detector-muon chamber tracks [2], thus improving the overall efficiency by a factor of $2-3$ for $\beta \gtrsim 0.6$.

Following the trigger selection, reconstructed final state quantities were used to select *R*-hadron events and suppress backgrounds, including (details are shown in Ref. [2]) :

- the transverse momenta of muon-like tracks (the background events tend to be softer),
- the ratio of high and low threshold HT/LT TRT hit multiplicities (owing to their β range the simulated *R*-hadron data peak at lower values of HT/LT),
- the distance $R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ between a *R*-hadron track candidate and a jet with $p_T > 100$ GeV (background muons are often associated or close to a hard jet while R is larger in average for *R*-hadrons),
- the cosine of the angle between two *R*-hadron candidates which both leave hard tracks in either the inner detector or the muon system $\cos\Delta\Phi$ (*R*-hadrons will be produced approximately back-to-back, unlike a number of background sources),
- the variable $\frac{q_{ID} p_{T,ID}}{q_\mu p_{T\mu}}$, where q_{ID} ,q_μ, $p_{T,ID}$, and $p_{T\mu}$ are the charge as reconstructed in the inner detector and muon system, and the reconstructed transverse momentum in the inner detector and muon system, respectively (as described in the previous section, the value of the *R*-hadron electric charge may be different in the inner detector and muon systems).

A candidate *R*-hadron must satisfy that no hard muon-like track ($p_T > 250$ GeV) can come within a distance $R < 0.36$ of a hard jet and fulfill at least one of the conditions listed below. For consistency the same selection is applied both for $R_{\tilde{g}}$ and $R_{\tilde{t}}$-hadrons though criteria 3-4 are only relevant for $R_{\tilde{g}}$-hadrons.

1. The event contains at least one hard muon track with no linked inner detector track. A linked track is defined such that the distance $R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ between the measurements in the ID and muon systems is less than 0.1.
2. The event contains two hard back-to-back ($\cos\Delta\Phi < -0.85$) ID tracks with the TRT hit distribution satisfying $HT/LT < 0.05$.
3. The event contains two hard back-to-back (as defined above) like-sign muon tracks.
4. The event contains at least one hard muon track with a hard matching ID track of opposite charge fulfilling the condition $p_{T,ID} > 0.5 p_{T\mu}$.

Table 1 shows the acceptance numbers and rates for the various samples. It can be seen that for *R*-hadron masses below 1 TeV ATLAS opens up a discovery window with integrated luminosity of the order of 1 fb^{-1} at 14 TeV center-of-mass energy. For masses above 1 TeV the rate of signal events is small, and is comparable to the expected background rate, so discovery would be challenging even with larger data-sets.

The event selection outlined above does not fully exploit the capabilities of the ATLAS detector : for instance, timing information was not used. Ongoing studies indicate that it is possible to measure the speed of the *R*-hadron candidates using time-of-flight information from the muon RPC and the Tile Calorimeter, with sufficient accuracy to enhance significantly the background rejection rate and, in the case of a discovery, to allow a measurement of the stable massive particle mass.

TABLE 1. Number of events selected for the given samples. Background samples not mentioned here are rejected by the selection.

Sample	**Accepted events**	**Rate (Events / fb^{-1})**
300 GeV gluino	235	6.44×10^3
600 GeV gluino	551	2.70×10^2
1000 GeV gluino	774	10.7
1300 GeV gluino	732	1.20
1600 GeV gluino	685	0.147
2000 GeV gluino	546	1.26×10^{-2}
300 GeV stop	78	70.0
600 GeV stop	134	3.9
1000 GeV stop	170	0.1
QCD	2	0.9
electroweak ($Z \to \mu\mu$)	1	0.8

CONCLUSION

Stable massive exotic hadrons (*R*-hadrons) are predicted in a number of SUSY scenarios. By exploiting the signature of a hard penetrating particle which may undergo charge exchange in the calorimeter and seemingly does not fall within a jet, ATLAS will be able to discover *R*-hadrons for masses below 1 TeV with relatively low amounts of integrated luminosity ($\sim$ 1fb^{-1}).

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